Assessing Variation in Implantable Cardioverter Defibrillator Therapy Guideline Adherence With Physician and Hospital Patient-sharing Networks

Erika L. Moen, PhD, Julie P. Bynum, MD,*† Andrea M. Austin, PhD,* Jonathan S. Skinner, PhD,*‡ Gouri Chakraborti, MA,* and Alistair James O'Malley, PhD*§*

Background: Implantable cardioverter defibrillator (ICD) therapy is used for primary prevention of death among people with heart failure, and new evidence in 2005 on its effectiveness changed practice guidelines in the United States.

Objectives: The objective of this study is to examine how the connectedness of physicians and hospitals, measured using network analysis, relates to guideline-consistent ICD implantation.

Research Design: We constructed physician and hospital networks for cardiovascular disease. Physicians were linked if they shared cardiovascular disease patients; these links were aggregated by hospital affiliation to construct a hospital network.

Subjects: Medicare beneficiaries who underwent ICD therapy for primary prevention from 2007 to 2011.

Measures: The clinical outcome of interest was guideline-consistent ICD implantation, calculated using the National Cardiovascular Data Registry. The exposure variables of interest were the network measures of the ICD surgeon, the referring hospital, and the hospital where the ICD surgery occurred.

Results: We focused on patients who were referred between hospitals for ICD implantation because they were more likely influenced by the hospital network (n = 28,179). Patients were less likely to meet guidelines if their referring hospital had more connections to other hospitals (OR, 0.49; 95% confidence interval, 0.25–0.96) and more likely to meet guidelines if their ICD surgery hospital had more connections (OR, 1.61; 95% confidence interval, 0.98–2.64). The ICD surgeon's network measures were not associated with guideline-consistent implantation.

Conclusions: Associations between the hospital network measures and guideline adherence suggests new approaches to better disseminate clinical guidelines across health systems.

Key Words: cardiovascular disease, implantable cardioverter defibrillator, physician network, hospital network, social network analysis

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The guidelines for implantable cardioverter defibrillator (ICD) therapy changed in 2005 after new evidence demonstrated their efficacy at preventing sudden cardiac death in heart failure patients with reduced left ventricular systolic function.[1–4] The potential for inappropriate shocks and high cost of these devices makes minimizing therapy in patients who are unlikely to benefit a priority for physicians, payers, and policy makers; however, variation in utilization and adherence to clinical guidelines exists across hospitals.[5–7]

Changing physicians' practice methods to follow new guidelines is a complex process that remains challenging for effective interventions.[8] Known barriers to guideline adherence among physicians include awareness, familiarity, and agreement.[9] These factors are likely influenced by the other physicians with whom a physician collaborates. Therefore, consideration of the physician as a member in a network, rather than as an isolated individual, may uncover novel, interpersonal factors that influence decisions regarding guideline adherence. Social network methodology can define a "physician network" composed of a set of physicians, the "nodes," and the relationships, or ties, between them.[10–16]

The theoretical framework for this study is that the physician network can identify prominent physicians and paths of communication that may influence practice patterns. Measuring objectively the strength of connections among physicians or hospitals in a way that accounts for the complex way in which networks can exist requires the social network methodologies applied in this study. Here, we use network methods to study the relationships between physician and hospital networks and guideline-consistent ICD implantations from 2007 to 2011. Using nationwide Medicare claims data, we created a "physician network" and a "hospital network"

From the *The Dartmouth Institute for Health Policy and Clinical Practice; †Department of Medicine, Geisel School of Medicine at Dartmouth, Lebanon; ‡Department of Economics, Dartmouth College, Hanover; and §Department of Biomedical Data Science, Geisel School of Medicine at Dartmouth, Lebanon, NH.

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Reprints: Erika L. Moen, PhD, 1 Medical Center Drive, HB 7251, Lebanon, NH 03766. E-mail: Erika.L.Moen@dartmouth.edu.

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based on the extent of shared cardiovascular disease patients. We attributed physicians to hospitals to capture the physician networks within hospitals to measure organizational and relational features of the physicians' care for patients within the hospital, while the "hospital network" measures interhospital patient-sharing ties. These networks capture the flow of clinical knowledge within and between hospitals. We hypothesize that the network position of physicians and hospitals will reflect their level of exposure to clinical information sources (eg, their connections to other physicians and hospitals involved in the care of their patients) and that such exposure may be associated with variation in adherence to medical guidelines.

Patients who are referred between hospitals are more likely to be impacted by the hospital network than patients who receive all of their care within 1 hospital, so we were specifically interested in how the network affects their likelihood of meeting ICD therapy guidelines. We used the physician and hospital networks to test the hypothesis that the likelihood of an ICD patient being within-guidelines is affected by the network characteristics of the physicians and hospitals involved in the decision-making and referral process.

METHODS

Overview of Methods and Approach

We performed a longitudinal, observational study of the association of guideline-consistent ICD placement in Medicare from 2007 to 2011. Using nationwide Medicare administrative data, we created the network of physicians who cared for cardiovascular disease patients, aggregated this network to create the hospital network and calculated network measures for each physician within their hospital and for each hospital in the national hospital network. We used the National Cardiovascular Data Registry (NCDR) ICD Registry to determine whether the individuals who received ICD therapy met guidelines. We then applied regression models predicting whether a patient who received ICD therapy met the clinical guidelines using novel predictors for three sources of clinical influence based on their network position: (1) the physician who implanted the ICD, (2) the patient's referring hospital system, and (3) the hospital where the ICD surgery occurred.

Overview of Data

The cardiovascular patient population used to inform the patient-sharing physician network included any Medicare patient who had full parts A and B coverage (12 mo or until death), did not have Medicare Advantage, and had ≥ 2 visits for any of the following cardiovascular diagnoses: arrhythmia, congestive heart failure, coronary heart disease, or peripheral vascular disease. We identified the set of physicians who cared for the patients in this cohort based on the billing provider for Evaluation and Management visits related to the same cardiovascular diagnoses.

The NCDR ICD registry was used to identify the Medicare beneficiaries who received ICD therapy. The ICD registry is a Center for Medicare and Medicaid Services (CMS)-mandated hospital registry for the in-patient setting that aimed to establish a national standard for understanding treatment patterns, quality, and outcomes for ICD therapy patients. Therefore, the number of hospitals that participated in the registry equals the number of hospitals that implanted ICDs during our study period. We linked ICD therapy patients from the NCDR ICD registry data to their Medicare billing data using unique beneficiary IDs.

We included hospital-level factors such as teaching status and the Rural Urban Commuting Area (RUCA) codes from the American Hospital Association and MedPAR and Provider of services data downloaded from CMS as covariates. We also obtained data on the ICD surgeons during our study period from Doximity, Inc. (https://www.doximity.com/). Doximity is a professional network site for health care professionals in the United States, with over 70% of US physicians as verified members. Doximity data has been used and verified in previous studies.[17,18] Indicators for clinical trial participation and publications for the ICD surgeons were included as covariates, because publication and participation in clinical trials may prime physicians for increased awareness of clinical guidelines.

This study was approved by the Dartmouth College Institutional Review Board, which also determined that informed consent was not required.

Attribution of Physicians and Patients to Hospitals

Physicians and patients were empirically assigned to hospitals using the physician hospital network methodology developed previously.[19] Physicians were assigned to the hospital where s/he submitted the most Medicare inpatient claims or, if they did not submit inpatient service claims, they were assigned to the hospital at which the plurality of their patients were admitted.[19] Patients were linked to primary care physicians who provided the plurality of their care and then to that primary care's hospital as in the Medicare Shared Saving Accountable Care Organization.[19,20] In this study, the patient's assigned hospital (based on the primary care physician) was considered the referring hospital. We identified the hospital that implanted the ICD by the hospital identifier in the ICD Registry.

Network Construction

In the following 2 sections, we describe our approach to constructing and analyzing the physician and hospital networks. A patient was linked to each physician who submitted an evaluation and management claim related to a cardiac care encounter with that patient from the Medicare physician/supplier part B claims file during the study period, and this formed a bipartite network between patients and physicians (patient-physician ties). We projected the bipartite network to form a unipartite physician network (physician-physician ties), where a tie between physicians existed if they shared at least 1 patient within the same calendar year.

Connections between pairs of physicians, or "dyads" were characterized by the number of visits with shared patients that occurred between them (for details see Supplemental Digital Content 1, http://links.lww.com/MLR/B532),[14,21,22] and any edge with a weight ≥ 1 was counted. Dyads with many patients in common are more likely to transmit medical opinions

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and information with the potential to persuade or influence medical practice than low or null (no patient-sharing) dyads.[21]

Network Measures

We calculated two network measures we hypothesized would impact a physician's or hospital's familiarity and adoption of new clinical guidelines. The first was a measure of the hospital's direct exposure and access to a broader range of clinical information sources (professional influence). Degree centrality counts the number of edges adjacent to the node of interest, and in the hospital network it represents how many direct connections (eg, patient-sharing relationships) the hospital has to the other hospitals. We interpret greater hospital degree as an indicator of increased access to a broader range of clinical information sources because of the higher number of ties that connect their hospital to others (Table 1). Next, we calculated an indicator of exposure to information flow, or the frequency with which the hospital is located on a common patient-sharing pathway between other hospitals (Table 1).[23] Betweenness centrality is defined by the extent to which a node is located on the shortest path (that is, fewest ties) between all other pairs of nodes in the network. In other words, if a hospital with high betweenness centrality is removed from the hospital network, the ability for one hospital to influence another is disrupted to a larger extent than if a hospital with low betweenness centrality was removed.[24,25]

To determine whether patients are typically referred from a lower to higher connected hospital in the network for surgery, we subtracted the degree of the patient's referring hospital from the degree of the ICD surgery hospital.

Network communities are groups of nodes (eg, hospitals) that have a higher probability of being connected to each other than to other members in the network. In our study, we are primarily interested in hospitals as a unit of service provider, not groups of hospitals, but we tested whether community detection may provide additional insights into the clustering of hospitals. Variation between hospitals explained by hospital communities, identified using the Louvain community detection method,[26] was close to zero. Therefore, we refrained from including it in the primary analyses (see results in Supplemental Digital Content 1, http://links.lww.com/MLR/B532).

The NetworkX algorithms in Python[27] were used to calculate network measures (described in the Supplemental Digital Content 1, http://links.lww.com/MLR/B532). The physician network was visualized using the Kamada-Kuwai algorithm[28] of the igraph library[29] in the R statistical software.[30] The hospital networks were visualized using the maps[31] and geosphere[32] libraries in R.

Selection of ICD Therapy Patients for Outcome Analyses

Because we were primarily interested in patients who were referred outside of their assigned hospital system for ICD therapy, we selected patients based on several factors (see the Appendix). First, we assigned each patient to the hospital that implanted the ICD by creating a crosswalk between the NCDR ICD Registry and the hospital IDs in our Medicare network. Any hospital where an ICD surgery occurred in a given year was considered "ICD-equipped." Second, each patient was attributed to a hospital based on their primary care, as described above,[19] which may or may not be ICD-equipped. If the patient's assigned hospital was not ICD-equipped, the patient was retained in the analysis and the assigned hospital is considered the "referring hospital."

TABLE 1. Definitions of the Network Terms and Outcome Measure

	Conceptual Definition	Operational Definition
Social networks analyzed		
Hospital network	Relationships among hospitals within the nation	A set of hospitals (eg, nodes) and the ties that occur between them (eg, edges), identified by physicians at each hospital sharing patients
Physician network	Relationships among physicians, in this context bounded by a hospital system	A set of physicians within each hospital and the ties that occur between them, identified by shared patients
Social network measures		
Measures describing the hospital's network characteristics within the nationwide network		
Hospital degree	The connectedness of a hospital in the nationwide network of hospitals	The number of ties the hospital has to other hospitals in the nationwide network
Hospital betweenness centrality	A measure of a hospital's exposure to information flow through patient-sharing practices in the nationwide network of hospitals	The number of times the hospital occurs on the shortest path between all other pairs of hospitals in the nation
Measures describing the physician's network characteristics within the hospital		
Physician betweenness centrality	A measure of a physician's exposure to information flow through a hospital system	The number of times the physician occurs on the shortest path between all other pairs of physicians in the hospital system
Primary outcome		
Adherence to ICD guidelines	A patient-level indicator of whether a patient with congestive heart failure who received ICD therapy was within-guidelines	LVEF $\leq 35\%$ and NYHA stage II or III

Conceptual and operational definitions are included for the social networks analyzed, the network measures calculated, and the clinical outcome of interest. Conceptual definitions of network measures represent the authors' interpretation of the measure in the context of health care systems and operational definitions of network measures state how the measure was calculated.

If the hospital was ICD-equipped the patient was excluded from the analysis, because these patients did not depend on between-hospital ties for surgery.

Finally, the patient was assigned to the ICD surgeon who performed the implant based on the National Provider Identifier (NPI) on the part B Medicare fee-for-service administrative claims data for the ICD implantation encounter. Although the referring physician may also be involved in the decision-making process, there is not a clear way to determine the referring physician for an individual patient from the claims data.

Outcome Variables

The outcome variable is guideline-consistent ICD implantation among patients with a diagnosis of congestive heart failure at the time of implantation. Using data from the NCDR ICD Registry,[33] we created the indicator for guideline-consistent ICD implantation if the patient had LVEF $\leq 35\%$ and NYHA Symptoms Class II or III. Although every Medicare beneficiary who received ICD therapy is included in the ICD Registry, people who may be eligible but do not receive an ICD are not recorded. Our outcome measure is therefore a measure of overuse, but not underuse, of ICD therapy.

Statistical Analyses

Statistical analyses were performed using the lme4 library[34] in the R statistical software. The effects of physician-level and hospital-level network measures on guideline-consistent ICD implantation were estimated using multivariable logistic regression models, adjusting for patient age, sex and race, descriptive characteristics of the hospitals (urbanicity, teaching status), network summary statistics for the physician networks within each hospital, and publications and clinical trial participation statistics of the ICD surgeon.

Random effects were specified to account for clustering of patients by their referring hospital and clustering of patients by the hospital where they received ICD surgery. The variances of the random effects provide insight into how much between-hospital variation remains unexplained after including hospital-level variables.

To guard against the outcome (ICD implantation) affecting the construction of the network, we also regressed the guideline-consistent ICD implantation among patients in year t+1 on the lagged hospital and physician network measures of year t.

We present the results as odds ratios (OR) by exponentiating the estimates of the regression parameters and of the end-points of the Wald 95% confidence intervals (CI). Thus, the OR represents the change in odds of being within-guidelines with a 1-unit increase in the network measure. Degree and betweenness centrality values were rescaled by 1 of 1000 and 1 of 10,000, respectively, to be on a similar scale to each other and other covariates in the model. To aid interpretation of the estimated odds ratios in the results, we note that when the baseline proportion of guideline-consistent ICD implantation equals 0.84 (the overall proportion in this study's patient cohort) an OR of 0.9, 1.0, 1.1, 1.2, and 1.5 approximately equals a difference of probabilities or risk difference (RD) of –0.015, 0, 0.012, 0.023, and 0.047, respectively.

RESULTS

From 2007 to 2011, 237,084 Medicare beneficiaries received ICD therapy and 156,682 were attributed to an ICD implanting surgeon and a hospital in our network (eg, shared at least 1 cardiovascular disease patient with another physician in the network). Of these patients, 28,179 were assigned to hospitals that were not ICD-equipped and thus dependent on between-hospital ties for the surgery (Table 2). We found that 4436 patients (16%) did not meet clinical guidelines: symptoms were too mild (NYHA Class I) in 961 patients to meet guidelines, too severe (NYHA class IV) in 1219 patients, and 2186 patients had an LVEF outside the recommended level.

Mapping Hospital and Physician Networks

Characteristics of all hospitals in the network are presented in Table 2. We visualized the hospital network with the hospitals located at their geocoordinates for the year 2011 in Figure 1A. Edges were weighted by the extent of patient-sharing between hospitals. Larger nodes correspond to hospitals with more ties to other hospitals (higher degree).

TABLE 2. Characteristics of Hospitals, ICD Implanting Physicians, and ICD Therapy Patients

	n (%)
ICD Therapy Patients in Study Cohort, 2007–2011 (N = 28,179)	
Out of ICD guidelines	4437 (16)
Age (median) (first, third q) (y)	73 (67,79)
Male	23,783 (84)
Race	
White	23,781 (84)
Black	3221 (11)
Other	1173 (4)
Urbanicity of assigned hospital	
Urban	14,807 (53)
Large town	6003 (21)
Small town	3444 (12)
Missing	3925 (14)
ICD implanting physicians for patients in study cohort (n)	3783
Cardiology as primary specialty	3136 (83)
Participated in any clinical trial	706 (23)
Publication count category	
None	428 (11)
Low (1-24)	1288 (34)
High (> 24)	414 (11)
Missing	1653 (44)
Betweenness centrality (median) (first, third q)	50 (6, 190)
Hospitals in network (n)	4653
ICD-equipped	1247 (27)
Teaching	246 (5)
Rural/urban code	
Urban	1746 (38)
Large town	670 (14)
Small town	1342 (29)
Missing	595 (13)
Degree (first, third q) (median)	164 (61, 352)
Betweenness centrality (first, third q) (median)	1347 (187, 5352)

Hospital characteristics represent all hospitals included in the nationwide network of hospitals each year. Physician characteristics are for physicians who implanted at least one ICD for a patient in the study cohort (ICD therapy patients whose assigned hospital is not ICD-equipped) in that year, obtained from Doximity Inc. Patient characteristics are for ICD therapy patients whose assigned hospital system was not ICD-equipped. Percentages may not add up to 100% due to rounding.

ICD indicates implantable cardioverter defibrillator.

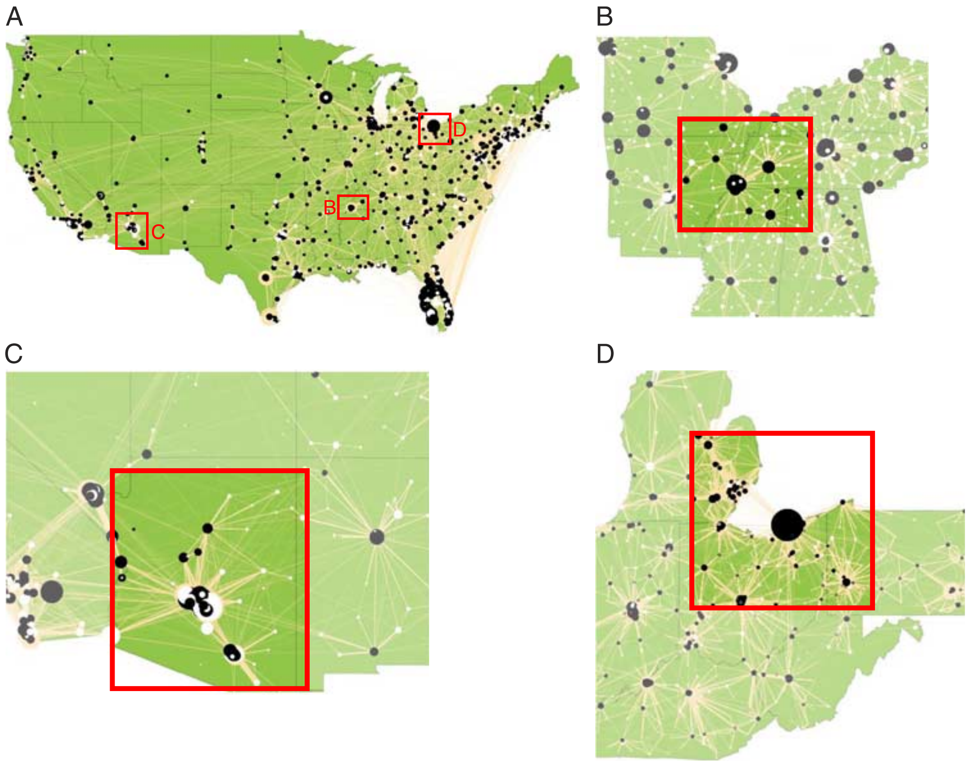

FIGURE 1. Illustrations of hospital networks. Hospitals are represented as circles (nodes) and ties between hospitals are weighted by the extent of patient-sharing among physicians at each pair of hospitals in the year 2011. ICD-equipped hospitals are colored black and referring hospitals are colored white. The size of the hospital node corresponds to the degree. A, For visualization purposes of the nationwide network of hospitals, only the top 10% of edges by weight linked to the hospitals in the top 25% of degree centrality are shown. Zoomed-in illustrations of the regions within the red boxes are depicted in (B–D). The size of the hospital node corresponds to the degree (B) and (C) and betweenness centrality (D). ICD indicates implantable cardioverter defibrillator.

To visualize the variation among different regional networks, we mapped in Figure 1B the network in an area with an ICD-equipped hospital (black) that has many connections (top quartile for degree) to referring hospitals (white) with low degree (bottom quartile). An alternative network structure is shown in Figure 1C by a region where the referring hospitals (white) are highly connected in the network. Figure 1D shows a region where an ICD-equipped hospital is on many common patient-sharing pathways (top quartile for betweenness centrality).

We also calculated the network measures for physicians within each hospital, and an example of such a network for one hospital is illustrated in Figure 2A. The edges between physicians represent the extent of patient-sharing that occurred between them. Larger nodes correspond to physicians located on common patient-sharing pathways among other physician dyads within the hospital.

Hospital and Physician Networks and Guideline-consistent ICD Implantation

Next, we investigated the associations between guideline-consistent ICD implantation and the network measures of 3 sources of clinical influence: the patient's referring hospital, the ICD-equipped hospital, and the ICD surgeon.

The connectedness of the patient's referring hospital was associated with guideline-consistent ICD implantation (Table 3): patients were less likely to be within-guidelines if their referring hospital had more connections to other hospitals (higher degree) (OR, 0.49; 95% CI, 0.25–0.96) and more likely to be within-guidelines if the hospital was on more common patient-sharing paths (higher betweenness centrality) (OR, 1.14; 95% CI, 1.00–1.30). These approximately translate to a risk difference of −0.12 for a 1-unit increase in the rescaled degree measure and 0.017 for a 1-unit increase in the rescaled betweenness centrality. Patients were more likely to meet clinical guidelines if the hospital where the surgery occurred had more connections (higher degree) (OR, 1.61; 95% CI, 0.98–2.64; Table 3), which approximately translates to a risk difference of 0.054 for a 1 unit increase in rescaled degree. We hypothesized that the combined effects of the degree of the referring hospital and of the ICD surgery hospital would relate to guideline-consistent implantation and found that the statistical test of whether both effects were equal to 0 was rejected ($P = 0.05$). Most patients were referred from lower to higher connected hospitals in the network (Fig. 2B). The ICD surgeon's network measures were not associated with guideline-consistent ICD implantation, although we did find that patients were more likely to adhere to guidelines if the surgeon's primary specialty was cardiology as opposed to other (primarily thoracic surgery).

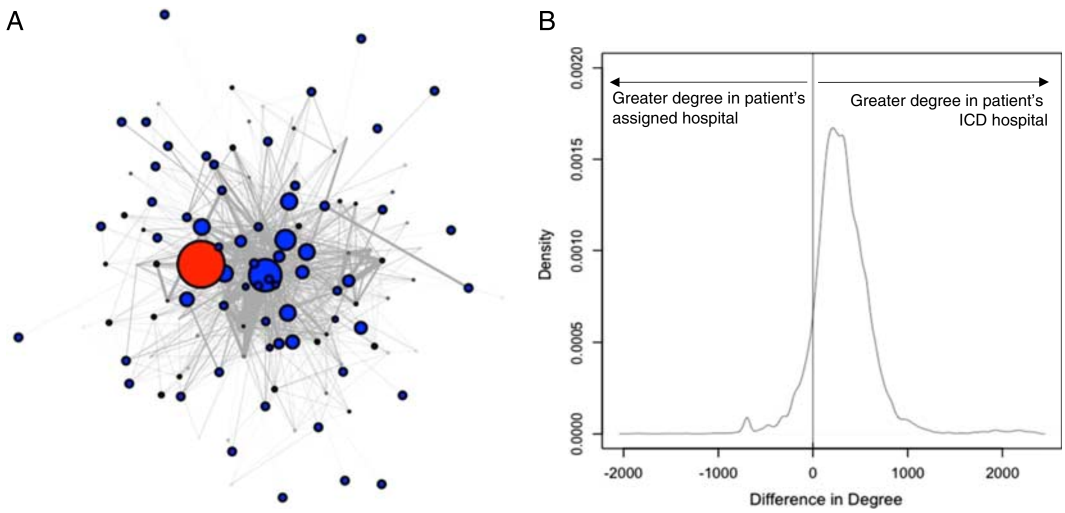

FIGURE 2. A, Illustration of a physician network. Nodes represent individual physicians who are connected to other physicians in the hospital with whom they share patients. The edges are weighted by the extent of patient-sharing between each physician dyad. The nodes are colored by whether the physician is capable of performing ICD surgery (red = ICD surgeon). Larger nodes correspond to physicians with greater betweenness centrality. B, Distribution of the difference in degree from the referral hospital to the ICD surgery hospital. The degree of the patient's referring hospital was subtracted from the degree of hospital where the ICD surgery occurred (ICD hospital). In this histogram, positive values correspond to patients who were referred to a hospital with higher degree (ie, more connected within the hospital network) for their ICD surgery. ICD indicates implantable cardioverter defibrillator.

TABLE 3. Association of Physician and Hospital Network Measures on Adherence to ICD Therapy Guidelines

	Concurrent Year Analyses		Lagged Year Analyses	
	Odds Ratio (95% CI)	***P***	**Odds Ratio (95% CI)**	***P***
ICD implanter (physician)				
Betweenness centrality	0.81 (0.18, 3.65)	0.785	2.25 (0.39, 13.16)	0.367
Cardiologist	1.77 (1.37, 2.29)	< 0.001	1.67 (1.24, 2.25)	< 0.001
Clinical trial count	0.99 (0.95, 1.04)	0.685	1.01 (0.96, 1.07)	0.623
Publication count category				
None	Referent	0.495	Referent	0.981
Low (1-24)	1.05 (0.91, 1.22)	0.408	1.00 (0.85, 1.19)	0.638
High (> 25)	1.09 (0.89, 1.33)		1.06 (0.96, 1.07)	
Assigned hospital				
Degree	0.49 (0.25, 0.96)	0.037*	0.61 (0.32, 1.16)	0.131
Betweenness centrality	1.14 (1.00, 1.30)	0.056	1.13 (0.97, 1.31)	0.106
Urbanicity				
Urban	Referent		Referent	
Large town	1.00 (0.85, 1.16)	0.961	0.98 (0.82, 1.16)	0.787
Small town	0.92 (0.76, 1.11)	0.359	0.90 (0.73, 1.11)	0.331
Teaching status				
Teaching	0.84 (0.62, 1.13)	0.245	0.99 (0.72, 1.35)	0.644
ICD surgery hospital				
Degree	1.61 (0.98, 2.64)	0.059*	1.67 (0.97, 2.89)	0.064
Betweenness centrality	0.94 (0.89, 1.00)	0.067	0.93 (0.87, 1.00)	0.049
Urbanicity				
Urban	Referent		Referent	
Large town	1.08 (0.76, 1.55)	0.660	1.07 (0.71, 1.60)	0.756
Small town	1.44 (0.37, 5.67)	0.602	1.24 (0.30, 5.08)	0.764
Teaching status				
Teaching	1.06 (0.88, 1.28)	0.567	1.05 (0.85, 1.30)	0.644

Results are presented for concurrent year analyses (left) and lagged year analyses (right).

*A 2-degree-of-freedom χ^2 test of the null hypothesis that the degree of the assigned hospital and the ICD surgery hospital jointly have no effect on guideline adherence was rejected ($P = 0.05$).

CI indicates confidence interval; ICD, implantable cardioverter defibrillator.

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The lagged year analyses comparing the network characteristics of the prior year to guideline-consistent ICD implantation found that the network of the ICD-equipped hospital system had the most robust effect over time (Table 3).

Finally, we examined whether clustering by the patient's referring hospital or the hospital where the ICD surgery occurred had a larger effect on between-hospital variation in guideline-consistent ICD implantation. The random effect variance for the hospital where the ICD surgery occurred was substantially greater than the random effect of the referring hospital (variance = 0.253 and 0.015, respectively) indicating that there is a greater amount of unexplained variation in guideline consistency between ICD-equipped hospitals than between the patients' referring hospitals.

DISCUSSION

We found the network prominence of hospitals to be predictive of the likelihood that a patient of theirs who receives an ICD was a guideline consistent case. Patients were less likely to meet clinical guidelines if their referring hospital had more connections to other hospitals, counter to our hypothesis. More connections may indicate more and disparate information flow by facilitating access to providers willing to recommend ICD therapy outside of clinical guidelines. Conversely, having fewer connections may allow for more reenforcement of information/referral paths and lead to improved learning. However, future work is needed to determine whether having fewer connections is a novel facilitator of increased guideline adherence for referring hospitals.

We also, however, found that patients were more likely to meet guidelines if the hospital where the ICD surgery occurred had more, not less, connections, though not a statistically significant finding. More guideline-consistent ICD implantations could be related to greater exposure to more experience by having a higher number and more diverse pool of referred patients. The associations reported, taken together, are consistent with the idea that regionalization of specialized services, in which peripheral hospitals refer to regional centers (eg, "hub and spoke"), are associated with greater guideline adherence (eg, Fig. 1B). Physician network position inside the hospital was not associated with guideline-consistent ICD implantation.

Previous studies have suggested an important role for procedure volume in explaining quality.[35–37] We adjusted for such differences by using random effects for the ICD surgery hospital, but still found that volume effects attenuated the magnitude of the ICD surgery hospital's network measures (but not the patient's referring hospital network effects). The problem with using volume as a covariate, however, is that it is endogenous to quality; higher quality hospitals tend to attract more patients.[38] For this reason, we rely instead on random effects to capture unmeasured quality differences across hospitals; under this approach, the data determines the extent to which effects are identified off variation within hospitals.

An important limitation is that we were only able to observe whether patients who receive ICDs are in line with guidelines, and thus cannot measure underuse, which occurs when patients who should receive the therapy do not. Also, Medicare patients may differ from non-Medicare patients in that they are somewhat more likely to meet ICD clinical guidelines, possibly due to Medicare's stricter reimbursement criteria and their greater underlying risk owing to their older ages.[39]

Our study adds to those that have primarily constructed large, inclusive networks of physicians regardless of disease specialty[14,21] or networks for only a single or few health care delivery systems.[11,12,21,40] As networks may only capture real signals related to the organization of care within specific medical domains, we aimed to construct a network specific to cardiovascular disease patients. Using Medicare billing data, we were able for the first time to create a nationwide network with patient-sharing pathways that have been previously shown to correlate with referral and advice-seeking relationships among physicians.[21] The sharing of patients across long distances, such as the distant connections with the Florida hospitals because of the snowbird effect (Medicare beneficiaries travel to Florida for part of the year and thus receive care by physicians in Florida and their home state) are particularly interesting to study because there is lower likelihood that connections of other types than patient-sharing are acting, such as being employed by the same hospital corporation, than are likely present for hospitals in close proximity.

Understanding the impact of physician and hospital networks may suggest novel strategies for disseminating new guidelines. For example, educational interventions on common patient-sharing pathways among hospitals may have widespread effects through the network. Future work could capitalize on the information gleaned from analyzing variation in quality of care outcomes with network methodology to improve dissemination of high quality clinical practice patterns.

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